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IXO and supernova remnants

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- Science drivers for X-ray observations of supernova remnants
- Current X-ray observations and open scientific questions
- Expectations from IXO

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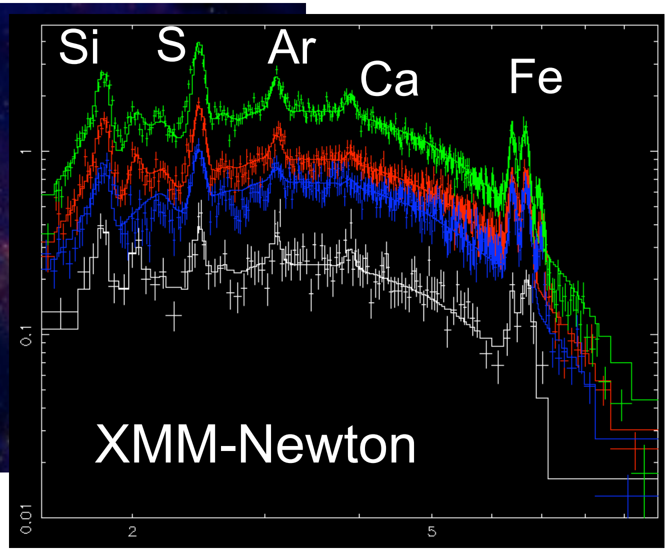
Supernova remnants : key ingredients to understand our Universe

Chemical enrichment, heating, turbulence and particle acceleration of the interstellar medium

- The origin of the heavy elements: composition and their dispersion
- The physics of supernovae: yields and explosion mechanism
- The physics of shocks: partitioning of the energy
- The origin of cosmic rays

=> supernovae and their remnants drive chemical evolution of galaxies

Hot diffuse gas in the Galactic center

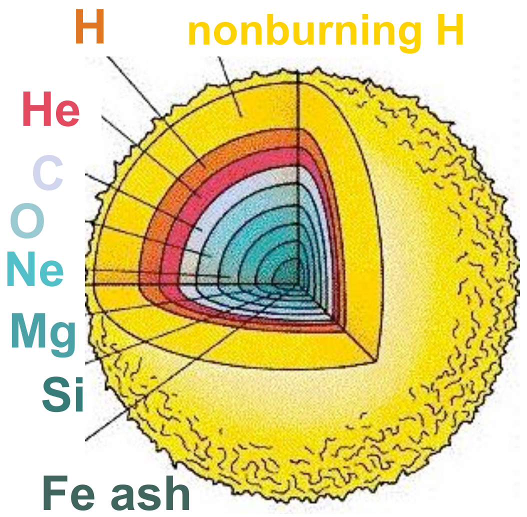


1. The origin of the elements : synthesis of heavy elements in stars

Hydrostatic nucleosynthesis in stars

- fusion of H to He (main sequence, millions years)
- fusion of He to C and O (giant stars)
- fusion of C, O, Ne to Mg, Si, S up to Fe (supergiant stars)

=> long timescale, classic onion-skin structure



Explosive nucleosynthesis in SNe

- most of heavy elements from Si to Fe peak
- only provider of elements heavier than lead and stable isobars

Very short timescale (s) **and large energy** (kinetic ~ 10^{51} ergs)

$\Rightarrow$ **much more diverse distribution of the elements**

Effective mechanism for dispersing them in the ISM

=> drive heavy-element enrichment of galaxies

2. The physics of supernovae: two main types of explosion

Quantity of synthesized elements depends on the type and on the detailed physics of the explosion

Thermonuclear supernovae: SN Ia

explosion of accreting white dwarf in a binary system when $M_{WD} > 1.4\ M_{\odot}$ via mass transfer

$\Rightarrow$ **total disruption of WD and complete ejection of synthesized elements**

- main provider of Fe (~75 %) and Fe peak nuclei.
- standard candles for cosmology

Open questions

- nature of the companion: normal star (single degenerate) or a white dwarf (double degenerate)?
- Ignition of the burning and burning front propagation ?

Quantity of synthesized elements depends on:

- accretion rate from the companion star
- physics of propagating flame fronts (slow / fast deflagration, transition to detonation)

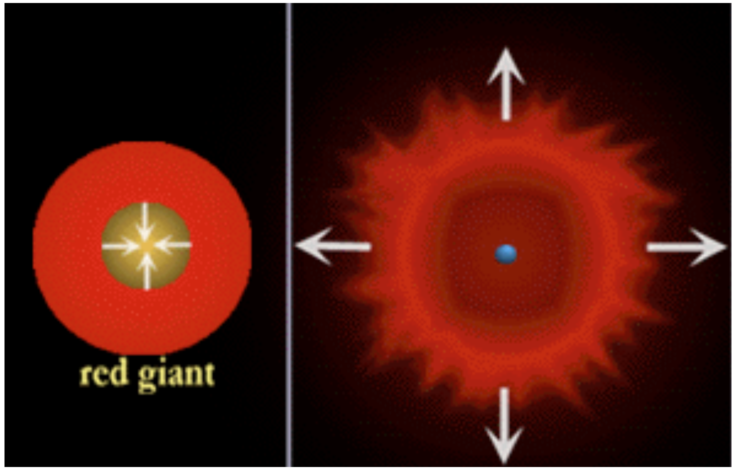
=> constraints from the observed ratio between intermediate elements and iron

2. The physics of supernovae: two main types of explosion

Core collapse supernovae: SN II, Ib, Ic, IIb, IIn

Gravitational collapse of Fe core of a massive star after successive stages of hydrostatic burning
=> neutron star / black hole and envelope ejection

- main provider of intermediate elements (Si-Ca): 70 %
- responsible for enrichment in very early universe



Open questions depending on the progenitor:

- Value of the mass-cut ? unclear on theoretical grounds
- Explosion mechanism: neutrino-driven, MHD-driven (jets)

Quantity of synthesized elements depends on:

- **progenitor** for element lighter than Si (essentially produced during hydrostatic evolution and spread away in the explosion)
- **explosion energy** and **amount of matter accreting** onto the core before the explosion for intermediate elements enhanced through explosive oxygen burning.
- **details of the explosion and mass-cut** between the residual compact object and the ejected envelope for iron-group nuclei

3. The physics of shocks: high mach number shocks

Overall kinetics: Rankine Hugoniot solutions to the equations of conservation and continuity

(McKee & Hollenbach 1980)

But unknown fraction of shock's kinetic energy that is transferred to thermal and cosmic ray population of electrons and ions

- From theory, T_e/T_p goes from m_e/m_p to rapid full equilibration
- From observation, intermediate degree of T_e/T_p and inverse relationship with shock velocity
- The inferred age, energy or distance of the remnant depends on the assumed T_e/T_p,

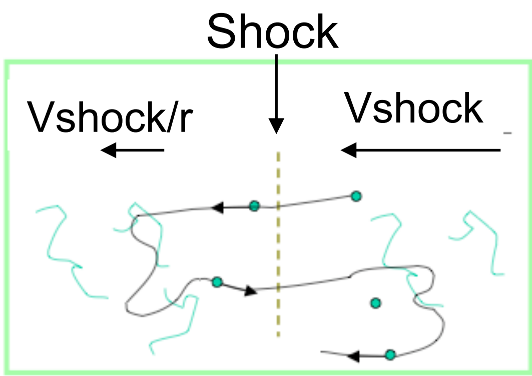
Open question: how is the shock energy shared between the different species (ions, electrons) at the shock?

Different measurements with various bias (see Rakowski 2005, AdSpR) from:

- **thermal X-ray bremsstrahlung** emission from the post-shock regions
- **thermal broadening** of a line
- **flux ratio of lines** of either a single element or between elements (optical : $H\alpha$, $H\beta$)

=> thermal Doppler broadening measurements in X-rays require spectral resolution: IXO

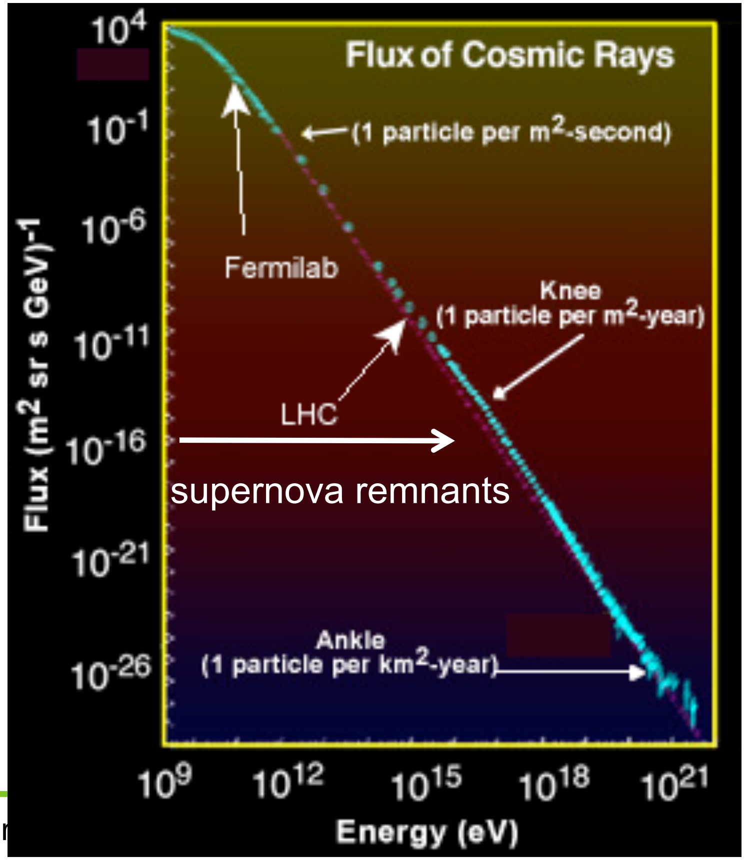
4. Physics of particle acceleration and the origin of galactic cosmic rays



First order Fermi acceleration

Supernova remnants: likely the birth places of Galactic CRs up to ~3 10^{15} eV

- 10% of their kinetic energy: to maintain the pool of Galactic Cosmic rays
- High mach number shocks: 1st order Fermi mechanism through diffusive shock acceleration (1949)

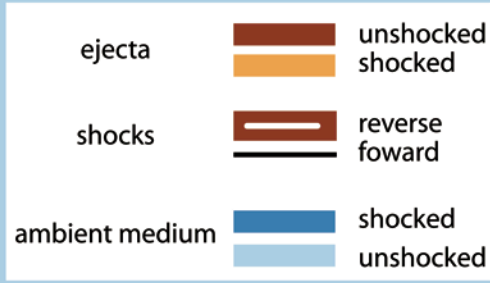


Objective : to understand the process of particle acceleration and the origin of Galactic cosmic rays

- What is the level of magnetic field amplification at the shock ?
- What is the maximum energy of the accelerated particles ?
- What is the efficiency of particle acceleration ?
- …

High energy: a predilection domain for observing Supernova Remnants

Supernova remnant

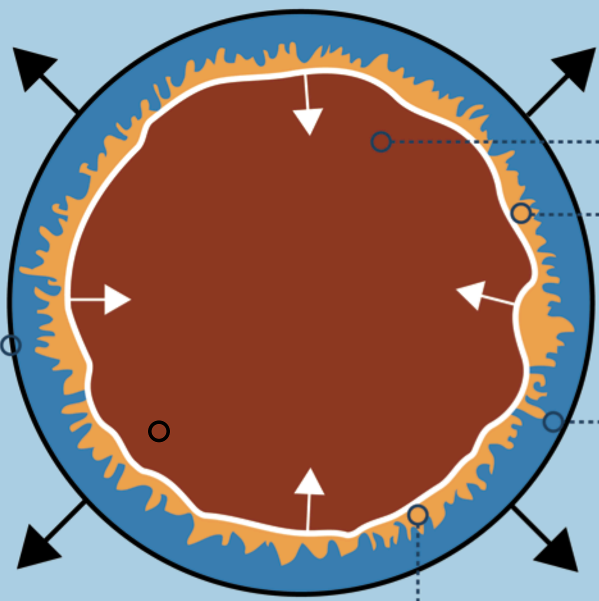


Particle acceleration at the shock

=> synchrotron emission from radio to X-rays

=> very high energy gamma ray emission: inverse Compton, pion decay

Fermi, HESS



Disintegration of radioactive nuclei in the ejecta

=> γ-ray emission

INTEGRAL

Heating of the ejecta by the reverse shock

=> X-ray thermal emission

Chandra, XMM-Newton, Suzaku

Heating of the ambient medium by the forward shock

=> X-ray thermal emission

Particle acceleration in SNRs: thermal and nonthermal emissions

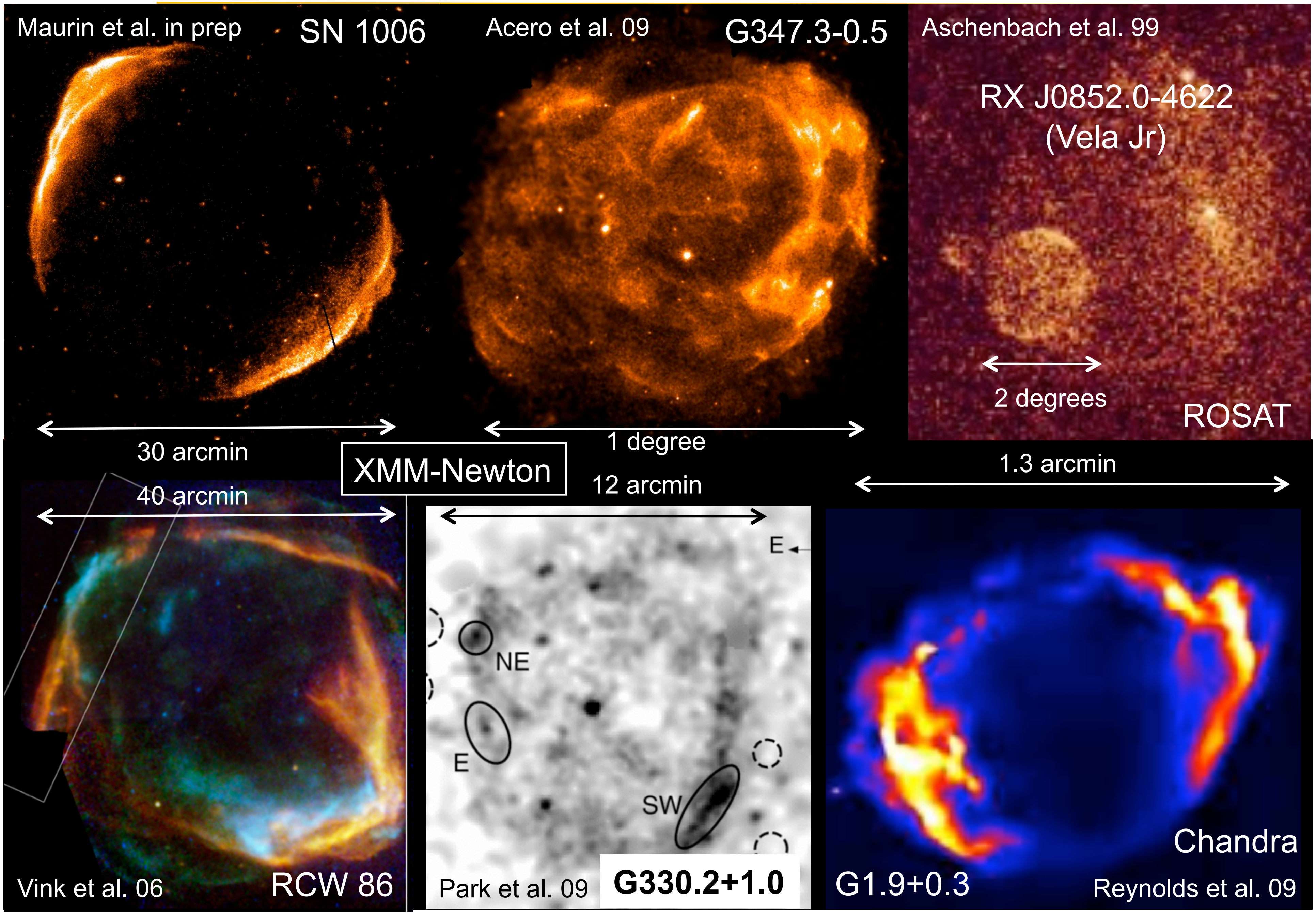
Radiative signatures at their shock:

- **Radio synchrotron** => electrons accelerated to GeV energies (Hanbury Brown 1954)
- **X-ray synchrotron** => electrons up to TeV energies in SN 1006 (Koyama et al. 1995, Nature)
- **TeV gamma-ray emission** => particles accelerated to TeV energies (Aharonian et al. 2004, Nature)

Why are X-rays crucial to investigate particle acceleration ?

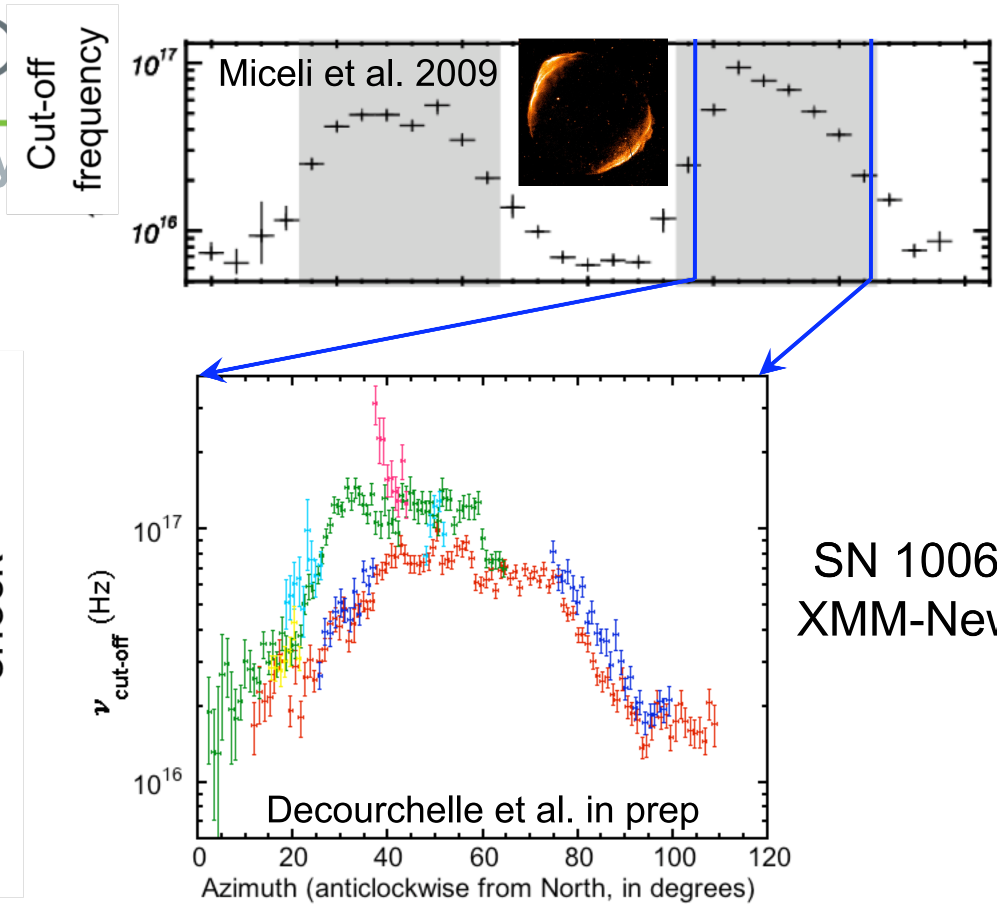
- Physics of the synchrotron emission of the electrons accelerated at the highest energy - the high energy end of the Cosmic Ray electron population -
- Physics of the thermal gas
  - Shock properties
  - Global parameters of the remnant : => downstream density => ambient density
  - Back-reaction of accelerated ions (protons) on the hydrodynamics
- Capability of performing spatially-resolved spectroscopy at small scale (< 10 arcsec)

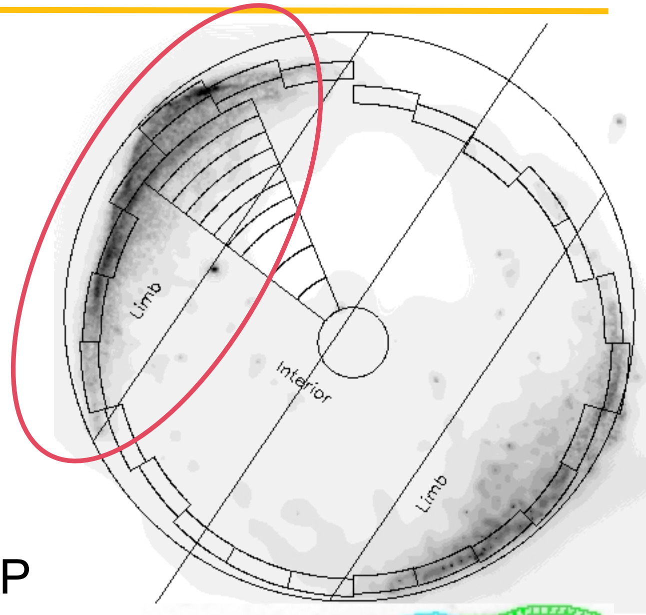
Synchrotron-dominated supernova remnants



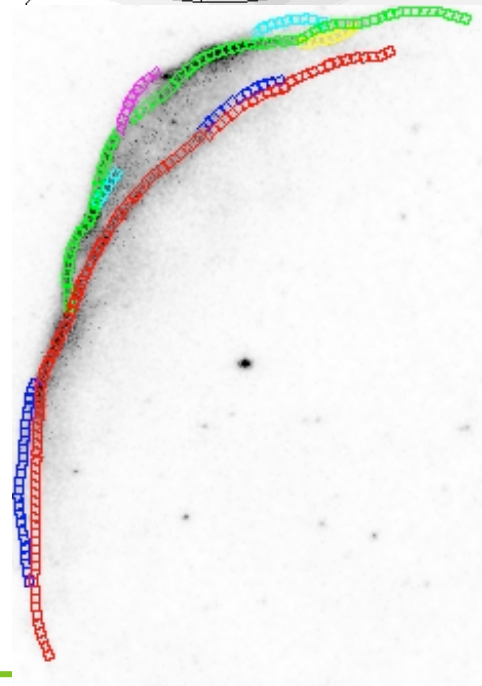
Properties of the acceleration: spatially-resolved spectroscopy

Synchrotron cut-off frequency along the shock



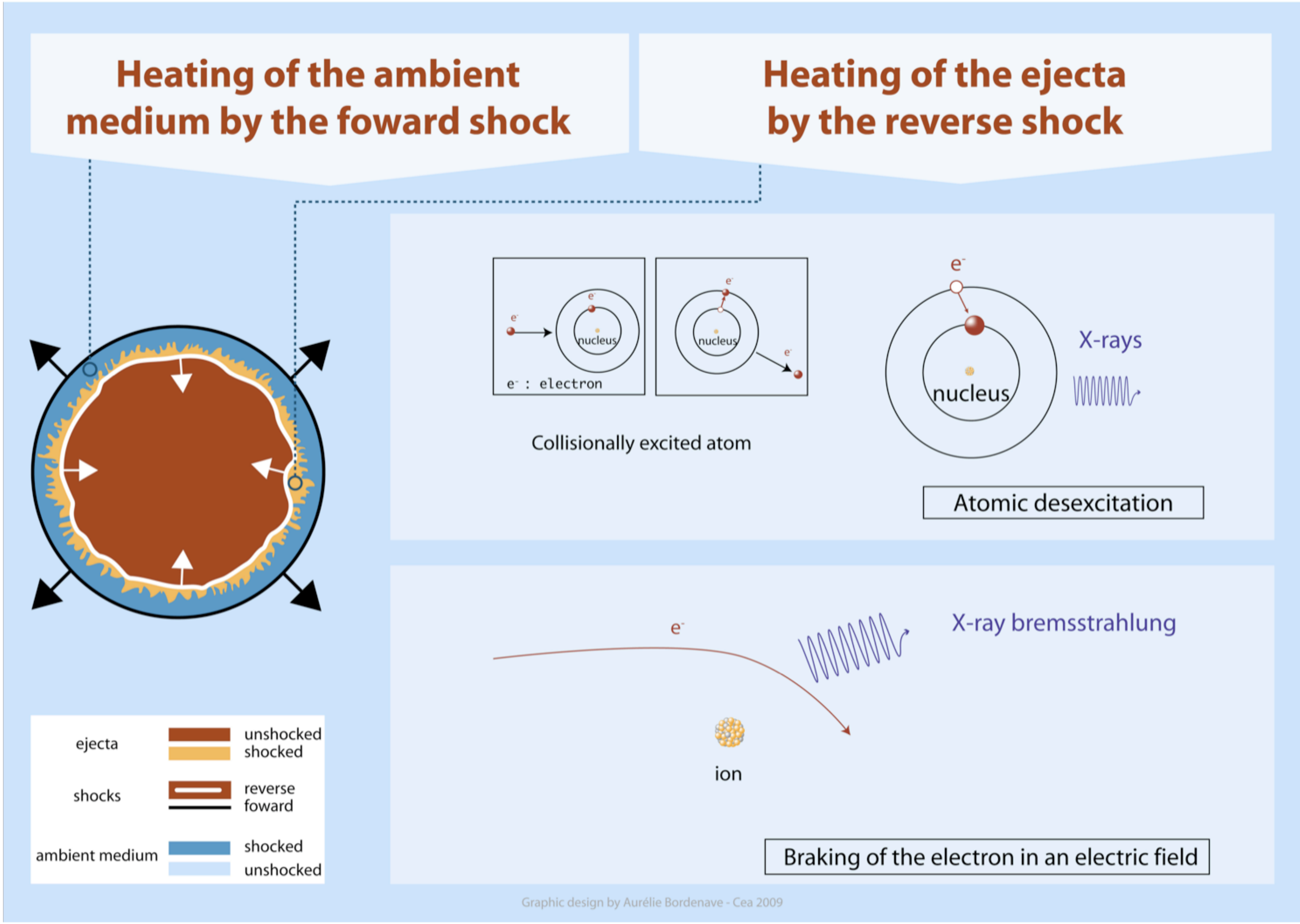


SN 1006 LP
XMM-Newton



- Measurement of the cut-off frequency $h\nu_{cut}$ (in X-rays)
- Estimate of downstream magnetic field

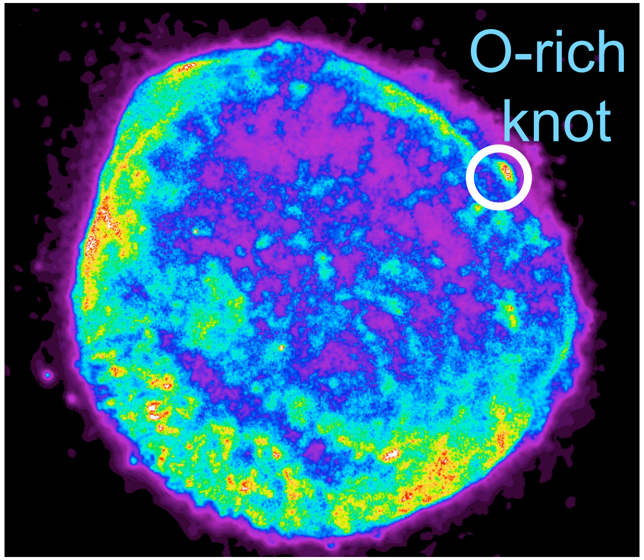
⇒ Estimate of the maximum energy of accelerated electrons : $E_{max} = 39\ (h\nu_{cut} / B_{10})^{1/2}$ TeV **~ few 10 TeV**

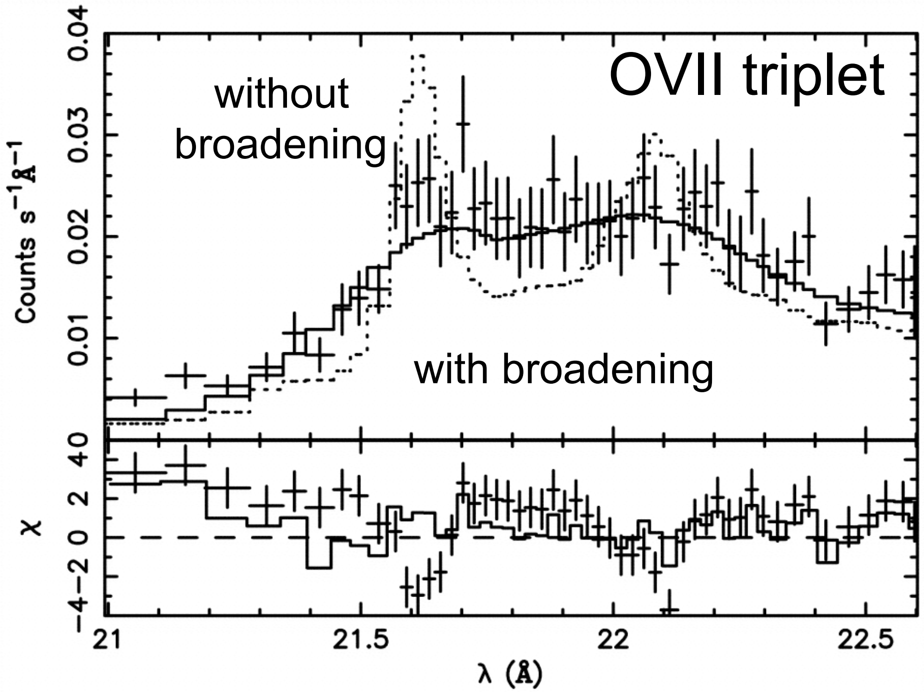

Heating of the ambient medium by the foward shock
Heating of the ejecta by the reverse shock
e-
nucleus
e- : electron
Collisionally excited atom
X-rays
Atomic desexcitation
X-ray bremsstrahlung
ion
Braking of the electron in an electric field
ejecta
unshocked
shocked
shocks
reverse
foward
ambient medium
shocked
unshocked
Graphic design by Aurélie Bordenave - Cea 2009

Shock physics

XMM-Newton RGS observation of the oxygen-rich knot in SN 1006

O K line band





Determination of oxygen temperature in SN 1006

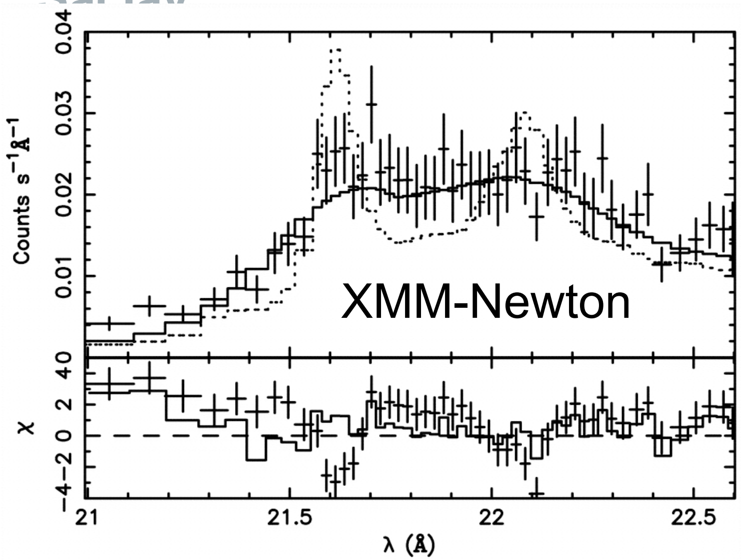
High resolution spectrum of the O knot in the Northwest of SN 1006 with the RGS
=> Doppler broadening of the OVII line measured :

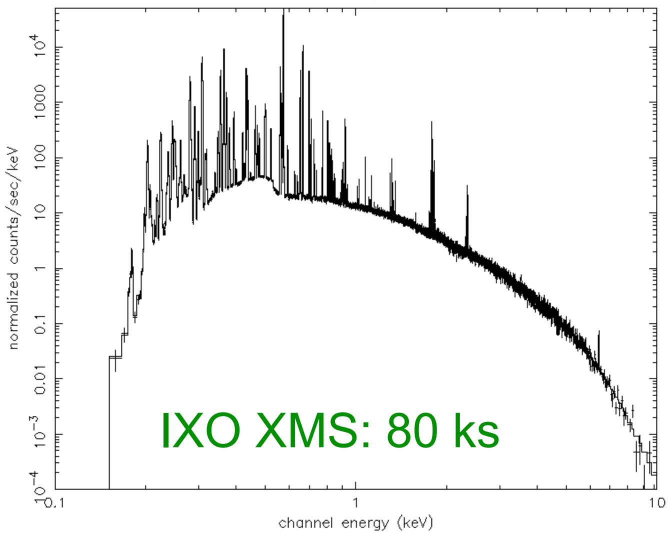
$kT_O = 528 \pm 150$ keV while $kT_e = 1.5$ keV

⇒ **Small degree of electron-ion temperature equilibration (< 5 %)**

(Vink et al. 2003, ApJL)

Measurement of the Oxygen temperature with IXO





XMM-Newton RGS:

σ_E= 3.4 ± 0.5 eV

kT_O= 528 ± 150 keV

kT_e = 1.5 keV

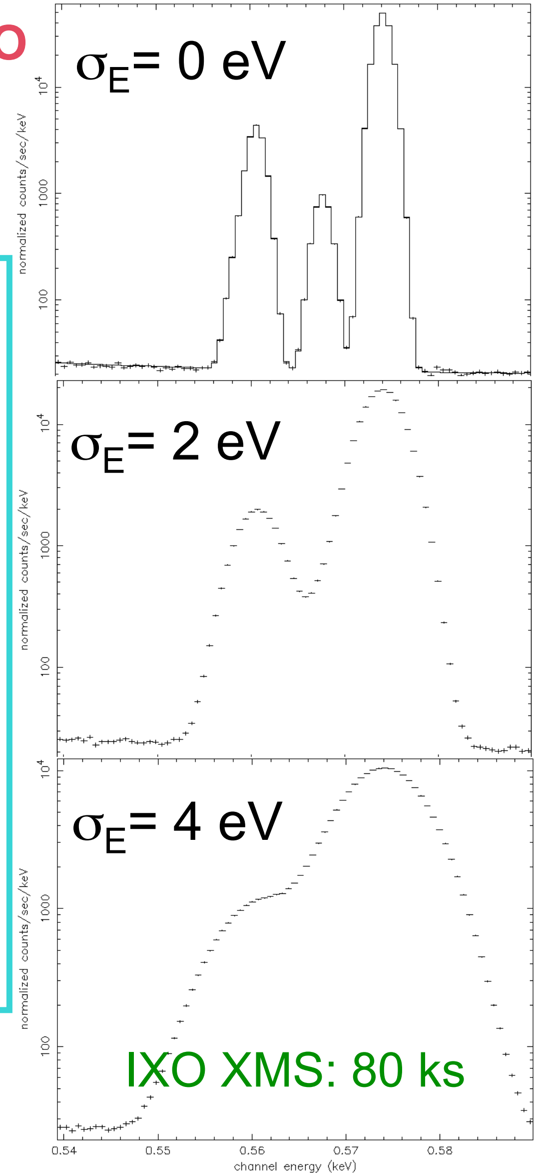
IXO XMS

σ_E ~ 2 [1.997-2.007] eV

kT_O~ 182 ± 1 keV

σ_E= 4 [3.983-4.009] eV

kT_O~ 730 ± 5 keV



OVII triplet

Shock physics and particle acceleration

Measurements of the post-shock electron and ion temperatures

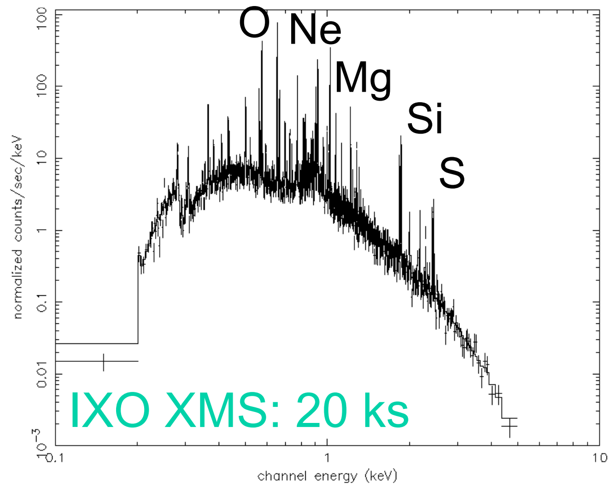
- Degree of electron-ion temperature equilibration
- Efficiency of ion acceleration through direct measurement of ions post-shock temperature.

Without efficient ion acceleration:

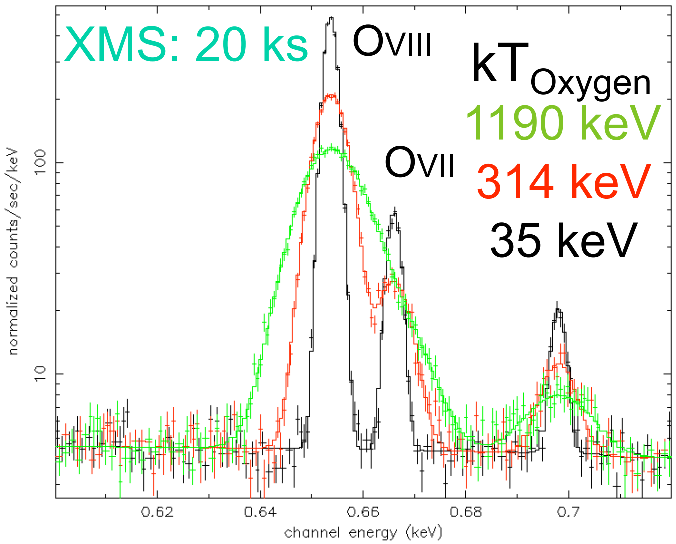
$kT_{\mathrm{Oviii}} \sim 1190$ keV

Much lower oxygen temperature if particle acceleration is efficient !

$kT_s < 3/16\ \mu m_p\ V_s^2$



Non equilibrium ionization model



Model with thermal broadening of the O lines

Origin of the elements and physics of the explosion

Direct measurements of the composition and spatial distribution of synthesized elements in the ejected material accessible through SNRs

OBJECTIVES

- to understand how heavy elements are produced, mixed and dispersed in the ISM
- to understand the explosion mechanism of stars and their progenitors
- to provide constraints to supernova models

How: by characterizing the emission from shocked and unshocked ejecta in young SNRs

Access to the elements synthesized by the supernovae: determination of the SN type

Access to the emitting conditions in the ejecta (density, temperature): constraints on progenitor and explosion mechanism

Access to the repartition and kinematics of the synthesized elements:

- level of mixing of elemental layers and asymmetry => understanding SN explosion
- level of mixing with the ambient medium => chemical enrichment in galaxies

For either type of explosion

- Intermediate elements (Si to Ca)
- Fe production
- Asymmetries/mixing of layers

are closely related to the explosion mechanism

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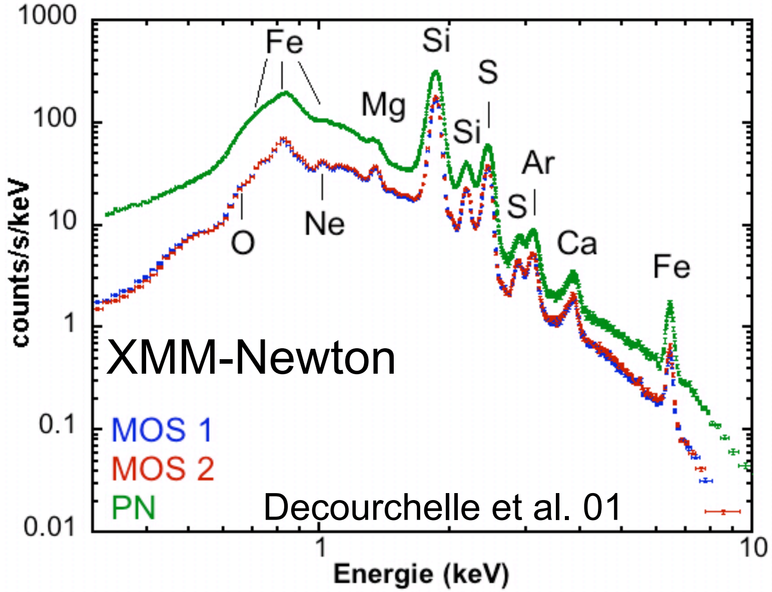
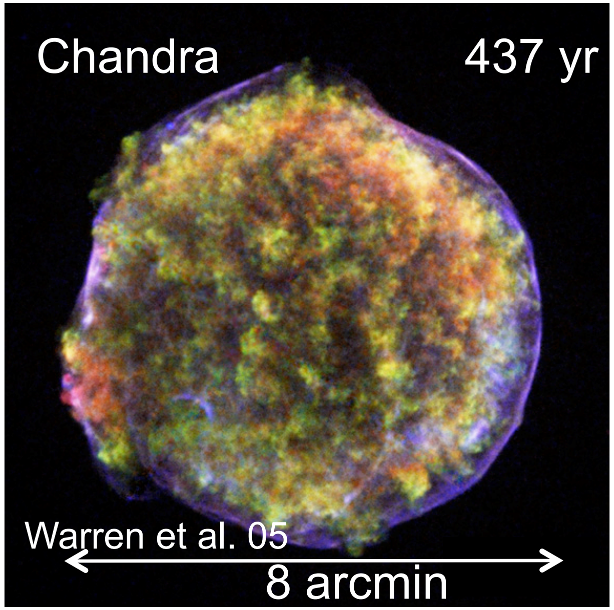
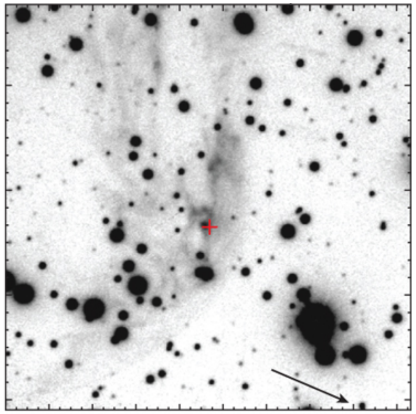
X-ray spatially resolved spectroscopy: a path to shocked ejecta

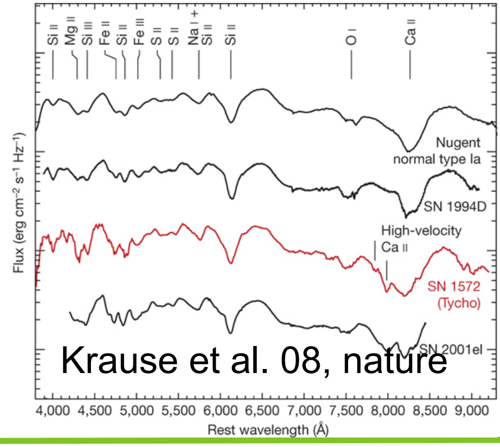
Tycho'SNR : an historical SN Ia supernova remnant (SN 1572)





Optical light echo image and spectrum of SN 1572 compared with spectra of normal extragalactic SNe Ia





X-ray spectra constrain SN type and explosion mechanism:

- delayed detonation favored for Tycho (Badenes et al. 06)
- normal type Ia confirmed by optical light echo spectrum (Krause et al. 08)

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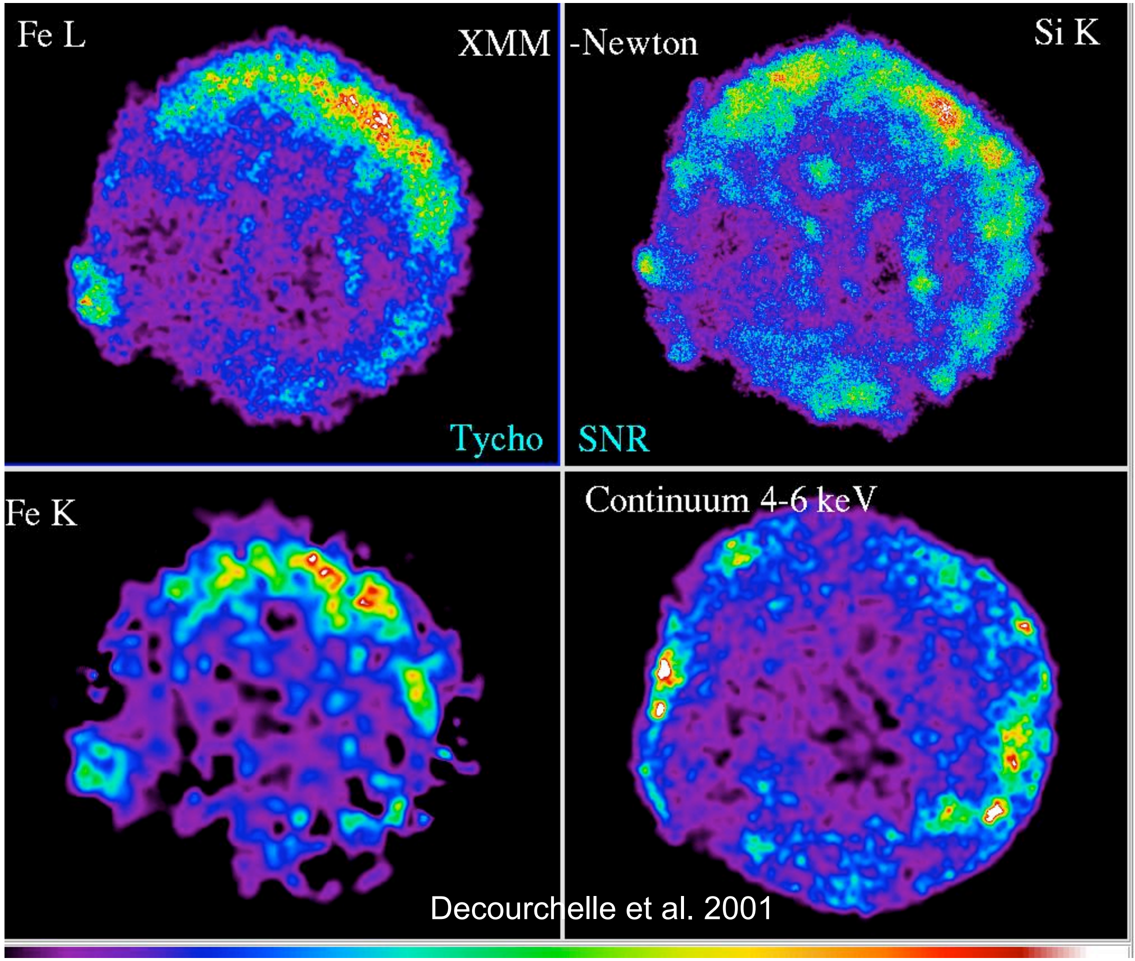
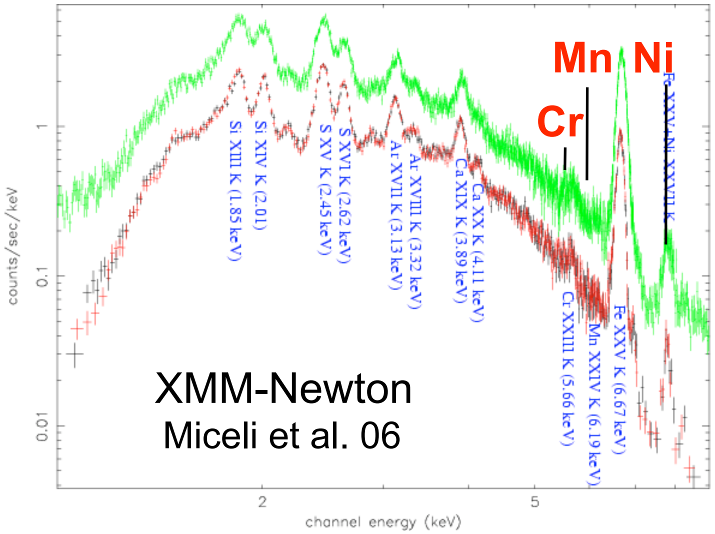
Spatial distribution of the elements synthesized in Tycho

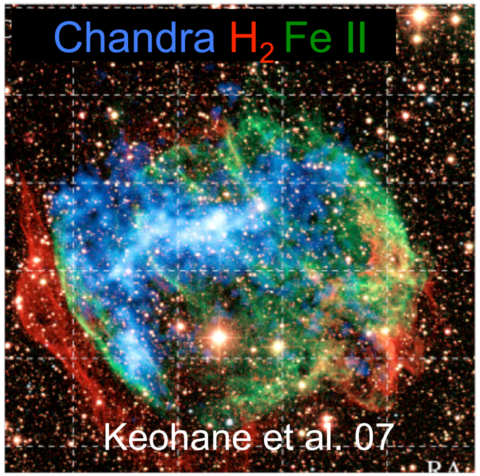


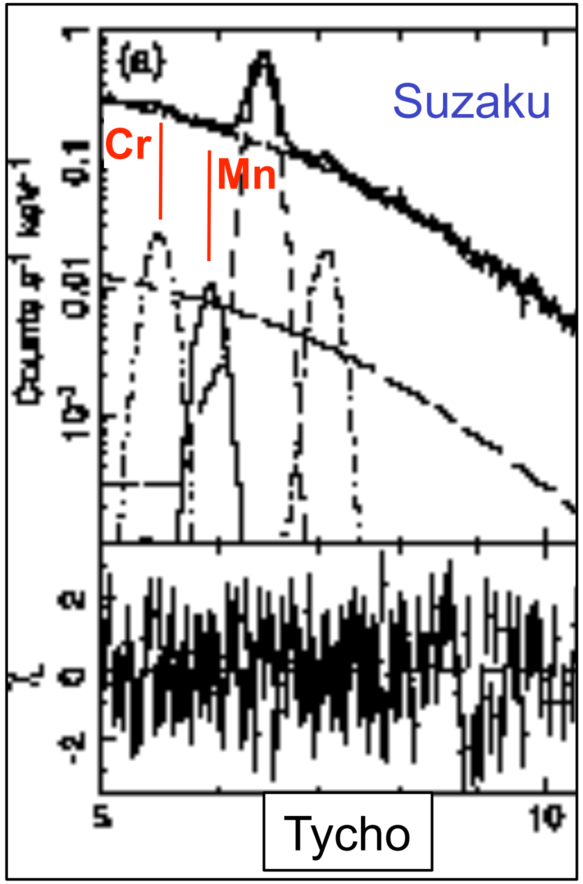
- Efficient overall mixing of the Si and Fe layers, but inhomogeneities at small scale.
- Fe K emission peaks at smaller radius than Fe L : higher temperature towards the interior
- Continuum emission associated with the forward shock (shown by Chandra to be nonthermal)

Presence of Cr and Mn Kα lines in the X-ray spectrum of young SNRs

W49B







- W49 B (ASCA, Hwang et al. 00, XMM-Newton Miceli et al. 06)
- Tycho (Suzaku, Tamagawa et al. 09)
- Cas A, Kepler (Cr only, Chandra, Yang et al. 09)

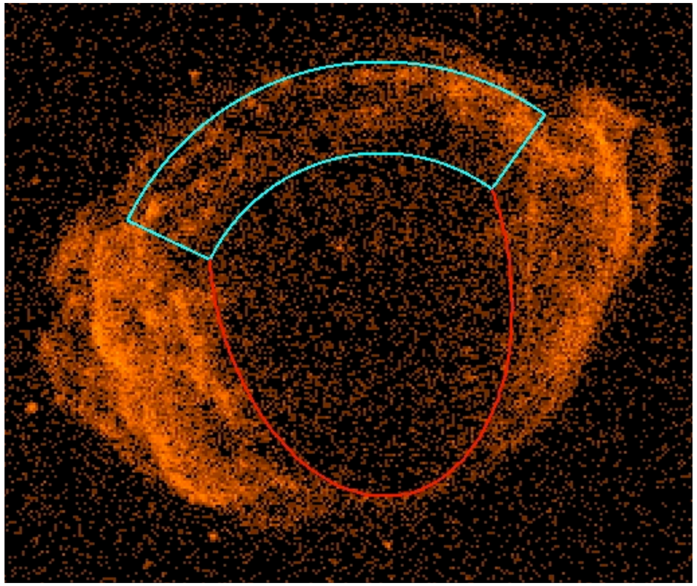
⇒ For type Ia, Mn / Cr is a promising tracer of progenitor metallicity (Badenes et al. 08, 09)

Radioactive decay in supernova remnants : ^{44}Ti

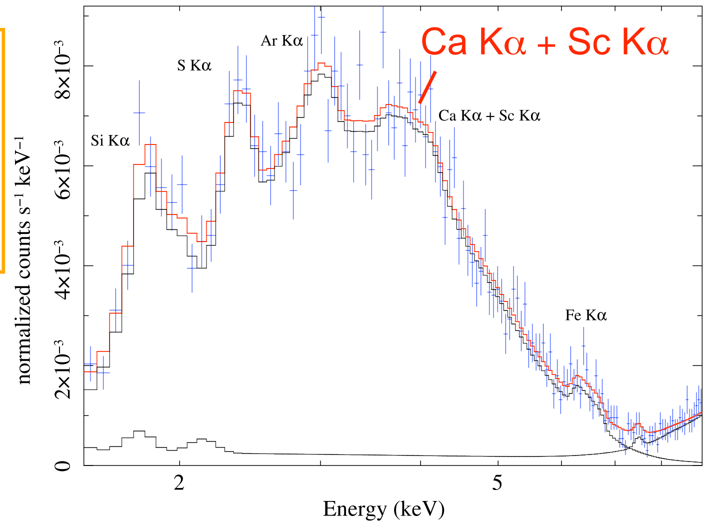
$^{44}Ti \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca$

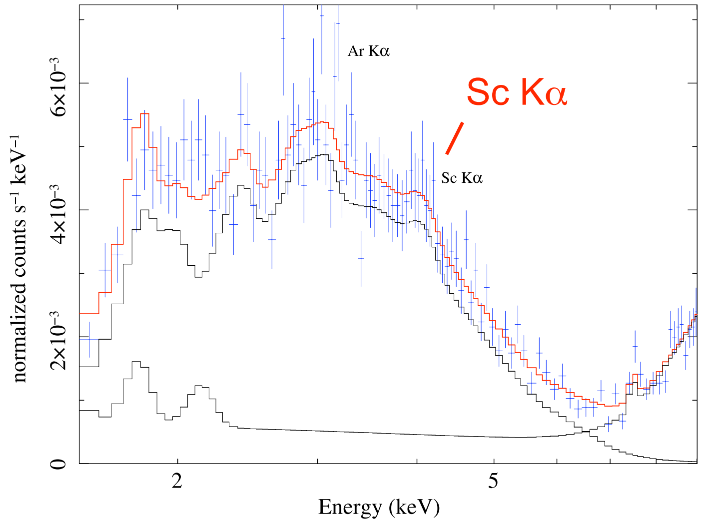
=> X-ray Kα lines of ^{44}Sc at 4.1 keV due to K-shell vacancies (Leising et al. 01)

- Claim of a possible detection in RX J0852.0-4622 (ASCA, XMM-Newton, Chandra) but infirmed by Suzaku (Hiraga et al. 09)
- Detection in the youngest known SNR G1.9+0.3 (Borkowski et al., 2010)



Chandra

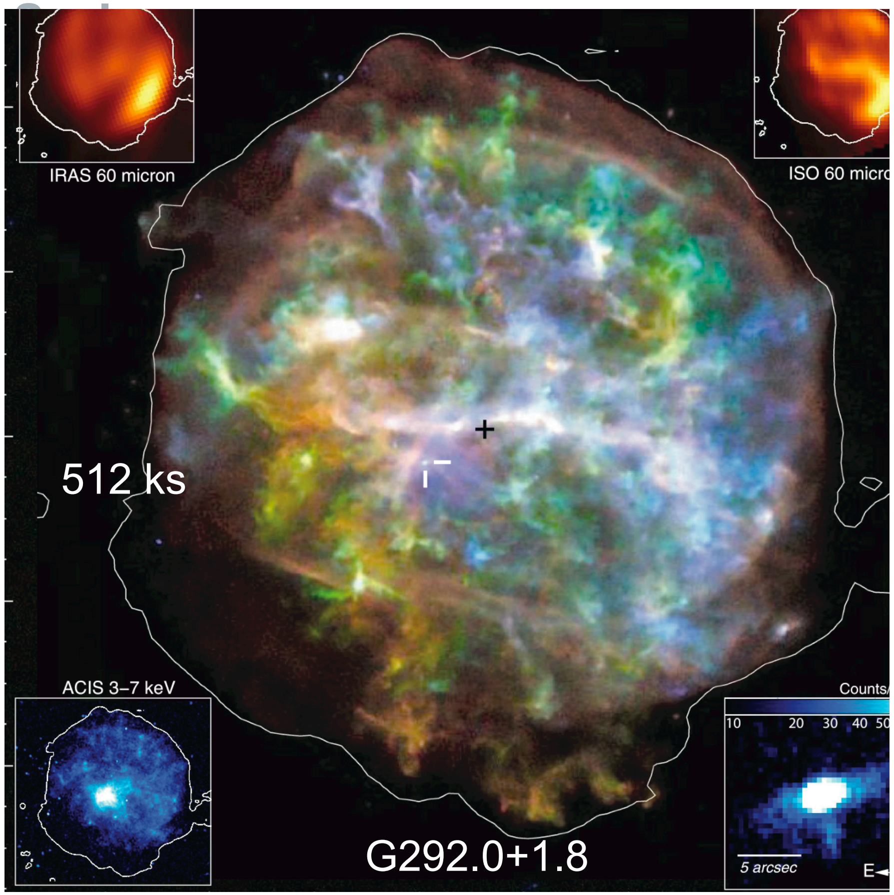


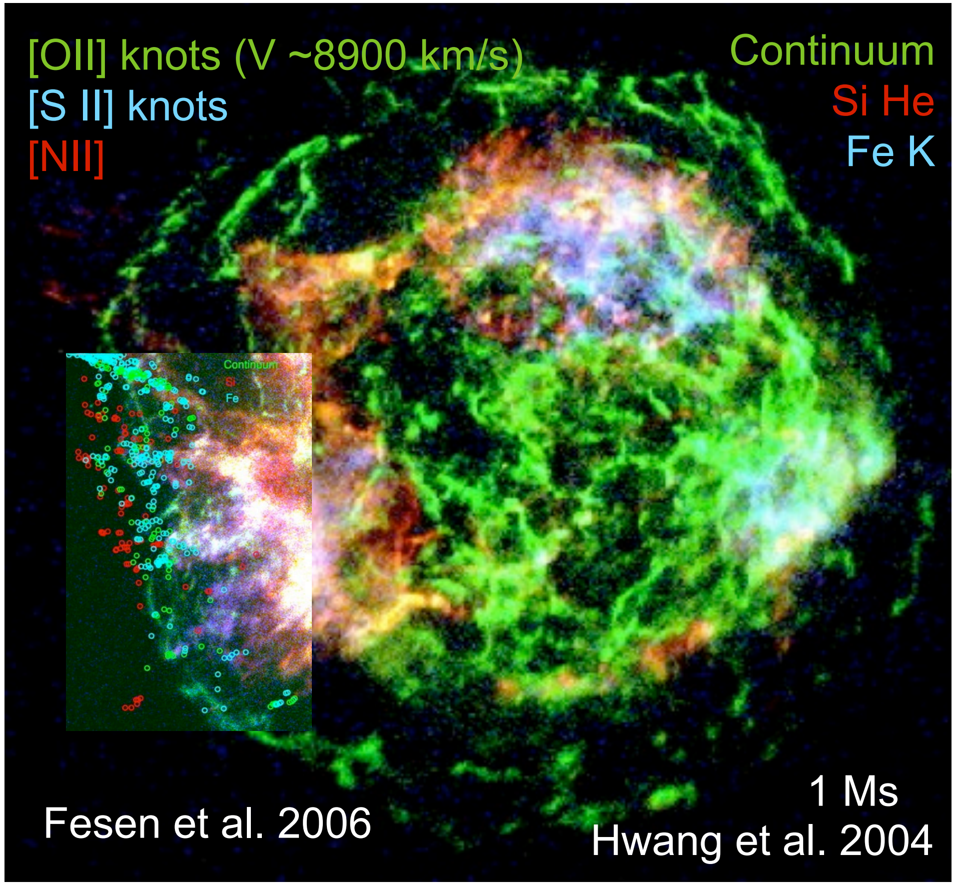


Difficult task with current X-ray sensitivity and spectral resolution = > IXO

Repartition of the synthesized elements in core collapse supernovae

- understanding of SN explosion (asymmetry, level of mixing of elemental layers)
- level of mixing with the ambient medium (chemical enrichment in galaxies)





Highly non-uniform distribution of thermodynamic conditions
=> asymmetric SN explosion ? (Park et al. 07)

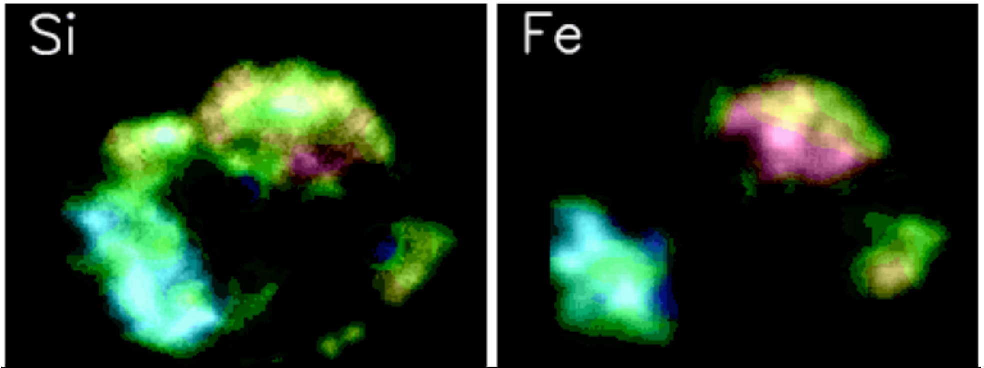
Highly non-uniform distribution of element
=> spatial inversion of a significant portion of the SN core (Hughes et al. 00)

Access to the kinematics of the synthesized elements

Understanding of SN explosion: asymmetry, level of mixing of elemental layers

Bulk motion of the ejecta through Doppler shift measurements

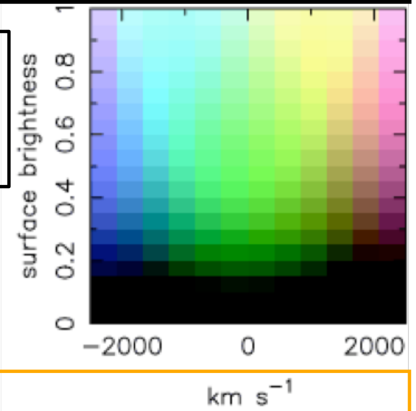
=> deep insight in the expansion of the ejecta and explosion mechanism through asymmetries and inversion of the nucleosynthesis product layers.



86 ks XMM-Newton observation of Cas A
(Willingale et al. 01)

- **Tycho :** 2800-3250 km/s for the iron shell (Suzaku, Furuzawa et al. 09)
- **Puppis A :** fast-moving oxygen knots at -3400 and -1700 km/s (Katsuda et al. 08)

Si-K, S-K and Fe-K Doppler shift maps
20” x 20“ images



Cas A:

- Velocities from -2500 to + 4000 km/s (Lazendic et al. 06, Willingale et al. 01, Hwang et al. 01)
- Line and Doppler images: spatial inversion of a significant portion of the Fe core
- Spatially resolved spectroscopy: abundance ratios~ core collapse of a 12 $M_\odot$ star (Willingale et al. 02)

Requirements for supernova remnant studies

Objectives: shock physics, particle acceleration and thermodynamic conditions, composition, spatial distribution and kinematics of the synthesized elements

Method: spatially resolved spectroscopy with high spectral resolution

Needs:

- 3D maps of the elemental composition and kinematics through Doppler shift measurements of various lines for a sample of SNRs => energy resolution must improve from ~100 eV to ~eV range.
- Increased effective area to perform spectroscopic studies at a relevant spatial scale, faint lines diagnostics (Cr, Mn, ^{44}Sc) and studies of a larger sample of SNRs including extragalactic SNRs in the local group

=> high throughput, high-resolution spatially resolved spectroscopy: IXO